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Key Points:
- Seismic waves could decrease besides increase the crustal permeability
- Decreases in permeability may depend on the earthquake azimuth
- The decrease in the permeability could be attributed to the clogging of fractures

Supporting Information:
- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3

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Seismic Waves Could Decrease the Permeability of the Shallow Crust

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Abstract Several experiments and field observations have demonstrated seismic waves-induced permeability increases. However, a few experiments have revealed significant decreases in the permeability of fractured sandstone after shaking produced by dynamic stresses. In this paper, we analyze the tidal responses of the water level in two wells (Junan and Dingyuan) situated on and near, respectively, the Tan-Lu fault in China. The results sampled by a single well indicate that seismic waves could both increase and decrease the permeability. In addition, our results indicate that the earthquakes that decreased the permeability in a single well were distributed in certain azimuthal zones. Given the azimuthal distribution of distant earthquakes, the observed permeability decrease could be attributed to the seismic wave-induced clogging of fractures that compose the flow paths in the shallow crust. Our research contributes to an enhanced overall understanding of the effects of earthquakes on the permeability of the shallow crust.

Plain Language Summary Most hydrological phenomena caused by earthquakes can be explained by permeability changes. Many experiments and field observations have demonstrated coseismic increases in permeability. However, coseismic decreases in permeability have seldom been reported. In this paper, we analyze the tidal responses of the water level in two wells. The results indicate that seismic waves could both increase and decrease the permeability. In addition, we find that the earthquakes that decreased the permeability in a single well were distributed in certain azimuthal zones. Given the azimuthal distribution of distant earthquakes, the observed permeability decrease could be attributed to the seismic wave-induced clogging of fractures that compose the flow paths in the shallow crust. Furthermore, we discuss the possible process of particle remobilization in a natural fracture network caused by seismic waves, as this process may be used to explain the azimuthal distribution of earthquakes that decreased the permeability. Our research contributes to an enhanced overall understanding of the effects of earthquakes on the crustal permeability. In the future, earthquake-induced increases and decreases in permeability should be considered when discussing controls on permeability for exploring underground resources of groundwater, geothermal energy, oil and gas, and for safely storing nuclear and toxic waste underground.

1. Introduction

Permeability is one of the key hydraulic parameters controlling fluid flow and transport in the crust. Variations in permeability change the discharge in streams and springs, modify production in petroleum reservoirs, and influence the strengths of faults and the crust by redistributing the pore fluid pressure (Faulkner et al., 2010; Hubbert & Rubey, 1959; Saffer, 2015; Townend & Zoback, 2000). Earthquake-induced enhancements in permeability have been widely observed in both the field and the laboratory (Brodsky et al., 2003; Elkhoury et al., 2006; Faoro et al., 2012; Ingebritsen, 1998; Manga & Brodsky, 2006; Shi & Wang, 2015). Various mechanisms, including the unclogging of fractures (Brodsky et al., 2003; Elkhoury et al., 2006), variations in the fracture aperture with fluid pressure (Faoro et al., 2012), and new fracture formation (Liao et al., 2015; Xue et al., 2013), have been proposed to explain the increases in permeability caused by dynamic stresses induced by the passage of seismic waves. In addition, some studies have indicated that earthquakes could decrease permeability (Shi et al., 2015, 2018; Yan et al., 2016). For example, the permeability in a fractured sandstone can potentially decrease under the effect of dynamic stresses (Liu & Manga, 2009; Shmonov et al., 1999). Similarly, a coseismic decrease in the discharge and temperature in a hot spring beyond the near field was attributed to an earthquake-

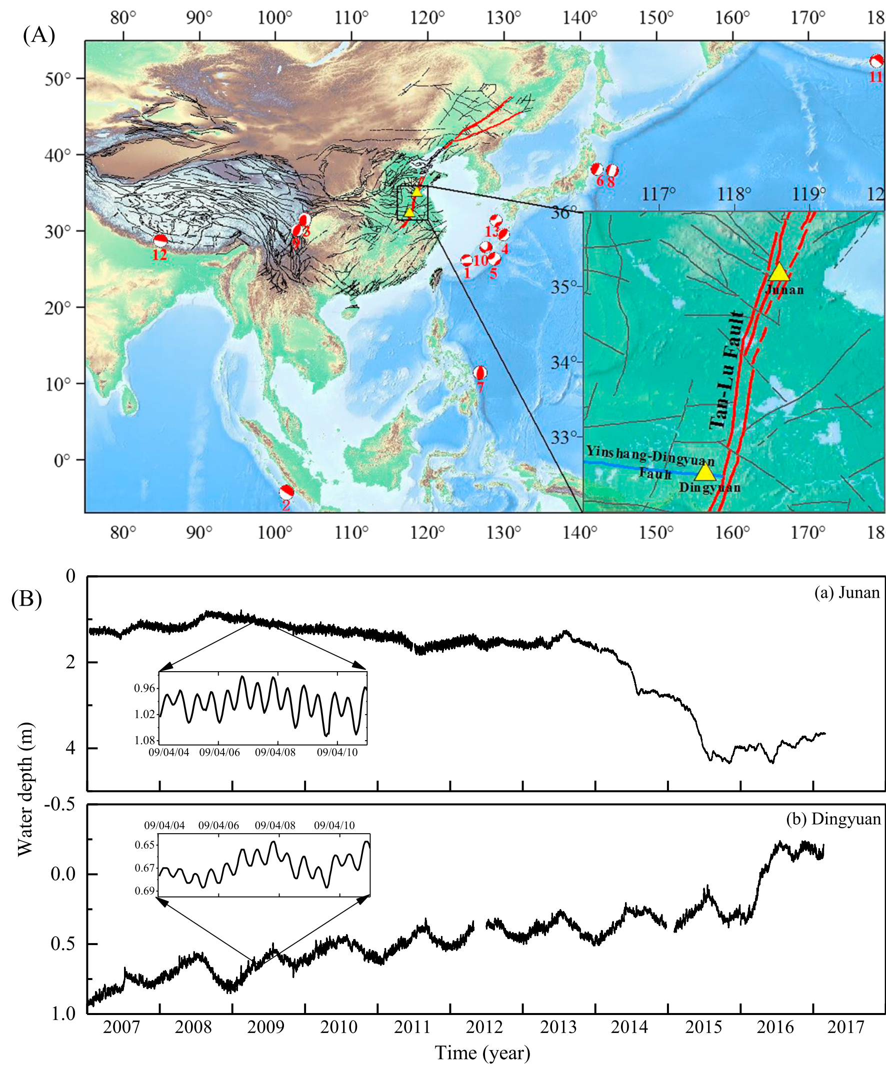

Figure 1. (a) Locations of the Junan and Dingyuan wells (yellow triangles) and the 13 earthquakes (beach ball diagrams with ID numbers; see Table S1 in the supporting information) that induced changes in the tidal responses of the water level with a seismic energy density exceeding 10^{-5}J/m^3, which is the statistical threshold for a hydrological response determined from worldwide observations (Wang & Manga, 2009). As local data are not available for reference, we use the theoretical seismic energy density (e), which is calculated via the empirical relationship derived by Wang (2007): $\log r = 0.48Mw - 0.33\log e - 1.4$, where r is the epicentral distance and Mw is the magnitude. This relationship is derived using data from southern California, though it may be approximately applied elsewhere in the absence of similar correlations. The red lines delineate the location of the Tan-Lu fault, while the blue line shows the Yinshang-Dingyuan fault, which intersects with the Tan-Lu fault. The insert shows the major active faults in the region surrounding the wells. (b) Water levels in the Junan and Dingyuan wells from 2007 to 2017. The inset shows an enlarged water level oscillation generated by solid Earth tides. For the Junan well, the variations in the water level slowly decrease after 2013 due to gradual clogging of the borehole. For the Dingyuan well, two segments of data are missing due to water level sensor failures. Steps and spikes in the water level within the Junan and Dingyuan wells caused by instrument malfunctions or maintenance are removed manually.

induced decrease in the permeability of the shallow crust (Shi et al., 2018). However, relatively scarce research, especially in the field, has been conducted on the mechanism of the earthquake-induced permeability decrease.

In this paper, we use the tidal responses of the water level in two wells as probes for the permeability and analyze the associated coseismic changes. Then, we propose a reasonable mechanism for the decrease in crustal permeability induced by seismic waves. Furthermore, we discuss the possible process of particle remobilization in a natural fracture network produced by seismic waves.

Table 1
Basic Information on the Two Wells

Well	Diameter (cm)	Depth (m)	Screened interval (m)	Sensor type	Aquifer lithology	Aquifer type	Distance to the Tan-Lu fault (km)
Junan	9.1	324	251.9-320.2	LN-3A	Limestone and igneous rock	Fissure-confined aquifer	[a]
Dingyuan	14.8	683.5	460-683.5	SW40-1	Red sandstone and conglomeratic sandstone	Pore-confined aquifer	24

Note. The distance to the Tan-Lu fault is measured from the well to the nearest segment of the main fault.
[a] The well is located on the fault.

2. Observations

The Tan-Lu fault is a major active strike-slip fault in eastern China that extends more than 3,000 km in a NNE-SSW orientation (Chen, 1988; Zhu et al., 2009); numerous earthquakes, including the 1668 Tancheng Mw 8.5 earthquake and the 1975 Haicheng Ms 7.3 earthquake, have occurred along this fault (Gao et al., 1988; Wang et al., 2006). Dozens of wells constructed as components of a nationwide network of groundwater monitoring wells in China are located on or near the Tan-Lu fault; these wells were designed to monitor possible changes in the water level that could serve as earthquake precursors. In this paper, we utilize two of these wells (the Junan well (35.2°E, 117.8°N) and Dingyuan well (32.5°E, 117.7°N); Figure 1 a and Table 1) that exhibit typical coseismic tidal responses and multiple changes (increases and decreases) in the phases and amplitudes of the tidal responses of the water level. The water level in the Junan well is recorded by LN-3A digital instruments with a sampling interval of 1 min, while the water level in the Dingyuan well is observed by SW40-1 instruments with a sampling interval of 1 hr. These sensors can record measurements ranging from 0 to 10 m with a resolution of 1 mm (Yan et al., 2016). Water level data collected from January 2007 to February 2017 are used to analyze the tidal responses in this paper (Figure 1b).

3. Tidal Analysis

In this study, the phases and amplitudes of the tidal responses of the water level were calculated with Baytap08 (Tamura et al., 1991). For the analysis, the water level data were divided into 30 day spans with an overlap of 23 days, and the parameter values discussed by Doan et al. (2006) were adopted for the tidal analysis. We used the M2 tidal component for the analysis because it exhibited the largest amplitude and the largest signal-to-noise ratio.

As shown in Figure 2, changes in the phases and amplitudes of the tidal responses in the Junan and Dingyuan wells were recorded at the times of earthquakes. In the Junan well, the phases and amplitudes synchronously increased in response to five earthquakes and decreased in response to four earthquakes. In the Dingyuan well, the phases and amplitudes transiently increased following four earthquakes and decreased following four earthquakes and there was a phase decrease with a corresponding increase in the amplitude response following the 2008 Wenchuan earthquake. The tidal responses to different earthquakes were not exactly identical for one well, and in most cases, the tidal responses to the same earthquake differed between the two wells.

4. Interpretation

Tidal responses of the water level serve as probes for studying the variations in crustal hydrogeological properties (Brodsky et al., 2003; Elkhoury et al., 2006; Ingebritsen, 1998; Manga & Brodsky, 2006; Shi & Wang, 2015; Xue et al., 2013; Yan et al., 2016). Generally, clear changes in the water level indicate that the aquifer is well confined (Xue et al., 2013). In addition, a negative phase response (<0°) is usually consistent with horizontal flow (Hsieh et al., 1987). Therefore, Hsieh's horizontal flow model is likely appropriate for the Junan and Dingyuan wells based on the variations in the water level (Figure 1b) and the tidal response (Figure 2) therein.

According to Hsieh's model, the transmissivity could be inferred from the measured phase and amplitude (Hsieh et al., 1987). As shown in Figure 3, in the Junan well, the permeability increased after five earthquakes and decreased following four earthquakes; these characteristics were seldom observed in the field

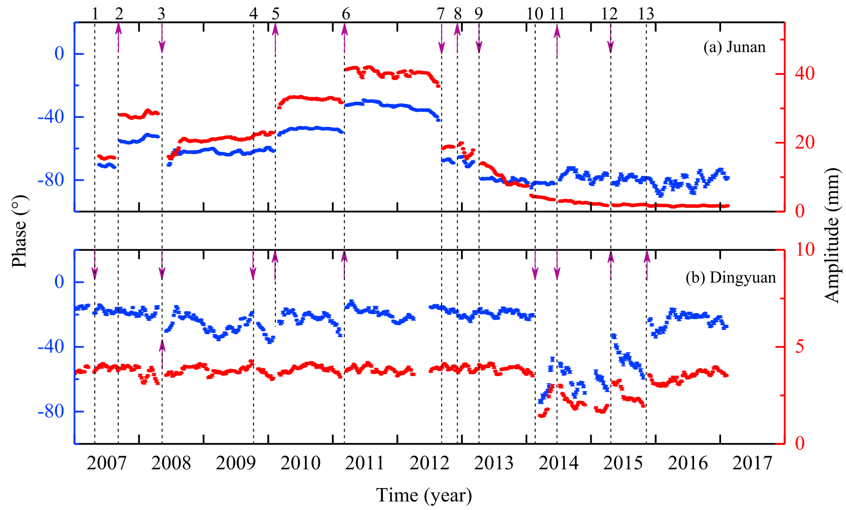

Figure 2. Tidal phase and amplitude variations in the Junan and Dingyuan wells over time. The red and blue error bars indicate the root-mean-square error of the tidal analysis. An earthquake is considered to have changed the tidal response if the coseismic variations in the phase and amplitude exceed twice the root-mean-square error. The vertical dashed lines correspond to the origin times of the 13 earthquakes with the same IDs listed in Table S1. The upward and downward arrows denote increases and decreases, respectively, in the phases and amplitudes induced by an earthquake.

in previous studies. In contrast, in the Dingyuan well, the permeability increased after four earthquakes and decreased following five earthquakes. Consequently, earthquakes not only increased but also decreased the permeability in these two wells.

5. Discussion

Both static and dynamic stresses are likely to cause permeability changes (Brodsky et al., 2003; Elkhoury et al., 2006; Liao et al., 2015; Manga et al., 2012; Manga & Brodsky, 2006; Rojstaczer et al., 1995; Shi & Wang, 2015; Xue et al., 2013; Yan et al., 2016). Since the static strain caused by an earthquake is too small

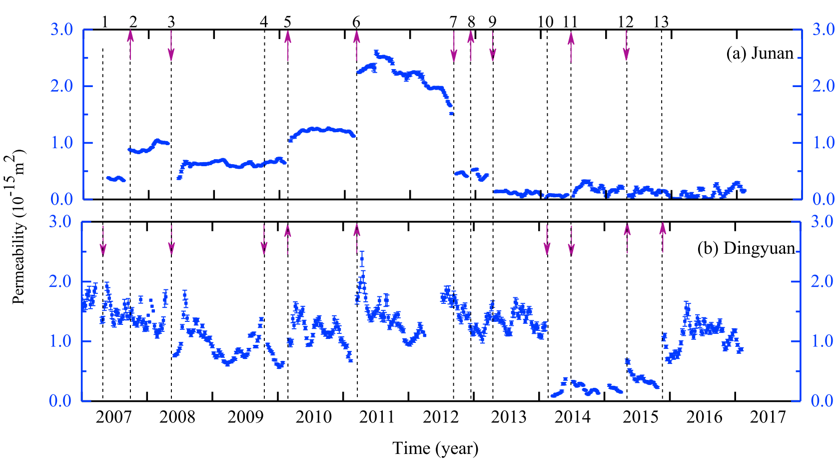

Figure 3. Changes in the permeability according to the tidal responses of the water level in the Junan and Dingyuan wells. The permeability k is related to the transmissivity (T) by $k = T\mu/\rho g d$, where μ is the fluid dynamic viscosity, ρ is the density of the fluid, g is the acceleration due to gravity, and d is the thickness of the open interval of the well. Using $\mu = 10^{-3}$ Pa·s at 20°C, $\rho = 10^3$ kg/m^3, and $g = 9.8$ m/s^2, for the Junan well, $d = 68.3$ m, for Dingyuan well, $d = 223.5$ m. Considering the weak sensitivity of the transmissivity solution to variations in the storage coefficient (Hsieh et al., 1987) and to minor variations in the storage coefficient (Xue et al., 2013), the transmissivity was estimated according to Hsieh's model (see the supporting information) with a fixed storage coefficient ($S=10^{-4}$; e.g., Liao et al., 2015; Xue et al., 2013). The errors in the permeability (blue error bars) were estimated by propagating the range of the phase errors.

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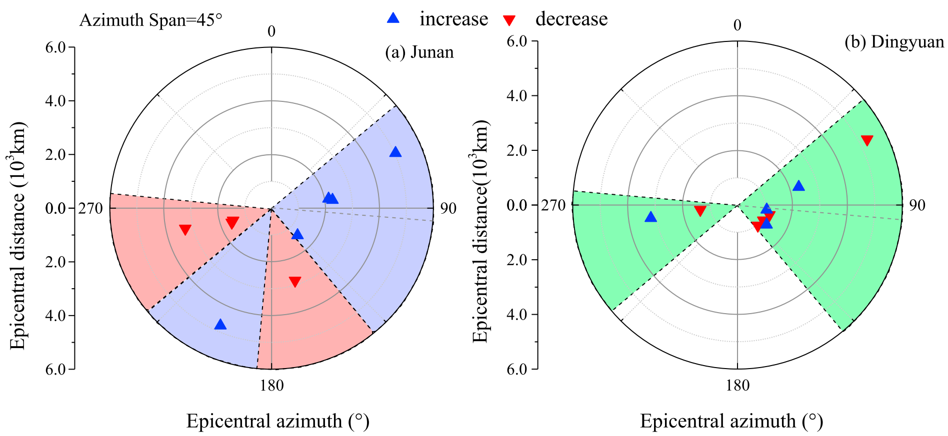

Figure 4. Distribution of the earthquakes that caused an increase or decrease in the permeability. The polar axis is the epicentral distance of the earthquake epicenter that corresponding to the well site and the polar angles are the corresponding epicentral azimuths. The blue and red triangles correspond to increases and decreases, respectively, in permeability induced by earthquakes. The blue, red, and green zones signify that an earthquake in the azimuthal zone may increase, decrease, and both increase and decrease, respectively, the permeability. The dashed line denotes the azimuthal span bound. During the period from 2007 to 2017, many earthquakes were distributed in the azimuthal range from 45 to 320° for these two wells. However, in the Junan well, the earthquakes that decreased or increased the permeability were distributed in different azimuthal zones, whereas in the Dingyuan well, they were distributed in the same or adjacent azimuthal zones (see Table S2 and Figure S1 in the supporting information). The seismic waves from distant earthquakes that decreased or increased the permeability were typically slow-decay and low-frequency surface waves, which have larger amplitudes than body waves and affect the water level. Thus, the azimuths of earthquakes could represent the azimuths of seismic surface waves. In other words, there may be an azimuthal dependence of the permeability decrease in the Junan well on seismic waves.

to change the hydrological properties in the shallow crust at epicentral distances exceeding 1,000 km (Table S1 in the supporting information; Manga & Brodsky, 2006; Manga et al., 2012), the permeability changes in the two wells should be attributed to the dynamic stresses created by the passage of seismic waves.

Various mechanisms, including fracture unclogging (Brodsky et al., 2003; Elkhoury et al., 2006), fracture aperture variations with the fluid pressure (Faoro et al., 2012), and new fracture formation (Liao et al., 2015; Xue et al., 2013), have been proposed for explaining the changes in permeability induced by seismic waves. For distant earthquakes with the epicentral distances exceeding 1,000 km (Table S1), the maximum dynamic strain (10^{-6}~10^{-5}; recalling that $\varepsilon = \sigma/K_u$, where the dynamic stress, namely, σ , is equal to ~0.06 MPa (Manga & Brodsky, 2006) and K_u is equal to 4–40 GPa (Wang, 2000) is too small to create new fractures. According to Faoro et al. (2012), seismic waves could change the permeability of fractures via fracture aperture opening or closure as the pore pressure in the fracture increases or decreases; however, the pore pressure, which is a scalar parameter, cannot be invoked to explain the azimuthal dependence of earthquakes that decrease the permeability (see Figure 4). Therefore, it is more reasonable to attribute the changes in permeability observed in the two wells to fracture unclogging induced by seismic waves.

Many studies have focused on the seismic wave-induced increase in the permeability. The unclogging of fractures has been regarded as a plausible mechanism for this permeability change. During the passage of seismic waves from distant earthquakes, deposits and colloidal particles may be removed from narrow constrictions in fractures that compose the flow paths by rapid oscillatory flow (Brodsky et al., 2003; Elkhoury et al., 2011; Manga et al., 2012), thereby increasing the permeability. Considering the mechanism of fracture unclogging as a reference, fracture clogging may be used to conversely explain the decrease in the permeability. Therefore, the wave-induced remobilization of deposits and particles in flow paths could cause a coseismic increase or decrease in the permeability of shallow crust.

A natural fracture network contains many fractures at various scales and orientations. Some fractures, known as conductive fractures, dominate the permeability of the fracture network. The responses of fractures to seismic waves arriving from a given azimuth may differ according to the fracture orientation (Crampin, 1984; Hudson, 1981). Accordingly, during the passage of seismic waves, wave-induced rapid oscillatory flow may occur in fractures with a certain orientation. Local flow could unclog fractures with this orientation, while connected fractures could become clogged due to accumulation and blockage by deposits and particles from the unclogged fractures. If the unclogged fractures are conductive fractures, the permeability of the fracture network may increase. In contrast, if the conductive fractures are clogged, the permeability of the network may decrease. Therefore, in a natural fracture network, the azimuthal distribution of earthquakes that decrease the permeability could be explained by the redistribution of deposits and colloidal particles in the conductive fractures induced by seismic waves. This further verifies the reliability of the fracture clogging mechanism in decreasing the permeability induced by seismic waves.

The aquifer exposed by the Junan well, which is on the Tan-Lu fault, is fractured (Table 1). In contrast, the aquifer exposed by the Dingyuan well, which is near the Tan-Lu fault, contains only a few fissures (Table 1). Hence, there is a difference of the fracture development between these two fields, and therefore, the azimuthal dependence of the permeability decrease on seismic waves may be associated with the state of fracture development in the shallow crust. However, further research on this azimuthal dependence of the permeability decrease on seismic waves requires additional detailed field data, especially data regarding the distribution of fractures and the structure of the fracture network in the study region.

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